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INSTITUTE OF SOLID MECHANICS, MECHATRONICS AND BIOMECHANICS
ÚSTAV MECHANIKY TĚLES, MECHATRONIKY A BIOMECHANIKY

CLASSIFICATION OF WEAR RELEVANT DUTY CYCLES OF TURBOCHARGER VALIDATION

KLASIFIKACE PROVOZNÍCH ZATĚŽOVACÍCH CYKLŮ TURBODMYCHADLA VE VZTAHU K OPOTŘEBENÍ KINEMATICKÝCH ČLENŮ

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Assignment Bachelor’s Thesis

Institut:	Institute of Solid Mechanics, Mechatronics and Biomechanics
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Supervisor:	**Ing. Petr Lošák, Ph.D.**
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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor’s Thesis:

Classification of wear relevant duty cycles of turbocharger validation

Brief Description:

Mechatronic components of the turbocharger exhibit various arts of wear (fretting, hammering, adhesive, abrasive etc.) depending on load conditions during its operation. As the usage of regular preventive means such as lubrication is not possible mostly due to thermal exposure of the components, the most contact pairs undergo dry contact with combined rolling and sliding motion. In order to ensure system robustness and durability over extended lifetime, an intensive validation plan has to be fulfilled for each design and each application. Results of the posttest analysis (PTA) then provide abundant source of data. To exploit the most possible information, data needs to be collected, sorted, reviewed and analysed.

Bachelor’s Thesis goals:

Gather test data from completed durability tests that are relevant for wear of kinematic components such as linkages, pins, valves, flaps and variable nozzles.
Review applied duty cycle and corresponding load cycle for the components for each test.
Define sorting factors and classify executed tests based on their severity, duration etc.
Propose and evaluate characterisation methodologies of load cycles targeting on expected resulting wear (load hysteresis, equivalent energy approach, friction power density etc.).

Recommended bibliography:

KROPÁČ, O. : Náhodné jevy v mechanických soustavách, Praha, SNTL - Nakladatelství technické literatury, 1987.

DOWLING, N. E. : Mechanical behaviour of materials, Prentice-Hall International Editions, 1993.

ONDRÁČEK, E., J. VRBKA, JANÍČEK P, BURŠA J.: Mechanika těles: pružnost a pevnost II, 4. přeprac. vyd. Brno: CERM, 2006, 262 s. ISBN 80-214-3260-8.

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In Brno,

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ABSTRACT

The present bachelor’s thesis aims to collect data from engine duty cycle tests, review it and determine criteria for its sorting. Furthermore, it also introduces and assesses characterisation methodologies for load cycles targeting expected resulting wear of turbocharger kinematics components. To evaluate and review the assorted data, two tools have been used: Python and Matlab. Finally, this thesis also proposes two methods that are the most suitable for processing duty cycles based on the evaluated data: a generic duty cycle data processing and a duty cycle analysis, including actuator position.

KEYWORDS

Turbocharger, VNT, wastegate, engine duty cycle, wear, data processing, validation

ABSTRAKT

Tato bakalářská práce se zabývá shromážděním dat z testů pracovního cyklu motoru, jejich kontrolou a určením kritérií třídění. Dále pak návrhem a vyhodnocením metodiky charakterizace cyklů zatížení, zaměřených na očekávané výsledné opotřebení kinematických komponent turbodmychadla. Vyhodnocení a kontrola dat jsou provedeny pomocí dvou nástrojů - Python a Matlab. Výstupem této práce jsou dvě navržené metodiky zpracování pracovních cyklů na základě zpracovaných dat - obecné zpracování dat pracovního cyklu a analýza pracovního cyklu, včetně polohy aktuátoru.

KLÍČOVÁ SLOVA

Turbodmychadlo, VNT, wastegate, pracovní cyklus motoru, opotřebení, zpracování dat, validace

ROZŠÍŘENÝ ABSTRAKT

Správná, věrohodná a ekonomicky efektivní validace v automobilovém průmyslu se využívá na úrovni subsytému nebo komponent. Příčinou toho je skutečnost, že dílčí součásti motoru pocházejí od různých dodavatelů. Vzhledem k požadavkům zákazníka na životnost, účinnost nebo náklady, validace těchto komponent hraje zásadní roli ve vývoji produktu. Vzhledem k tomu, musí být komponenty před sériovou výrobou testovány. Není tomu jinak ani u validace turbodmychadla, které vyžaduje mnoho hodin testování z důvodu ověření, zda je daná komponenta kompatibilní s operačním prostředím. Měřením na motoru se z testů získávají kvanta dat o pracovním cyklu motoru, jako jsou například informace o otáčkách motory nebo kroutícím momentu. Bohužel tato data pocházejí z různých zdrojů, například od zákazníků nebo dodavatelů. Můžeme se pak setkat s různými názvy a jednotkami pro tyto veličiny, také délka časů se liší. Není proto možné klasifikovat tento test pouze na základě vytvoření grafů, protože o něm nemáme dostatnečné informace.

Cílem této práce je shromáždit a posoudit tyto testy, definovat třídící faktory, navrhnout a zhodnotit metodiku charaktetizace cyklů zatížení, zaměřené na očekávané výsledné opotřebení kinematických komponent regulačního systému turbodmychadla. Na základě znalostí o prostředí pracovního cyklu motoru můžeme předpokládat naměřené veličiny, které budou obsaženy v každém testu. V našem případě předpokládáme, že otáčky motory, zatížení motoru a čas, budou obsaženy ve většině testů.

Práce je rozdělena na dvě části. První část je zaměřena teoreticky. Nejdříve jsou zde rozebrány možnosti regulace a regulační systémy turmodmychadla, včetně představení aktuátorů, které ovládají tyto systémy. Právě zde se objevují kinematické komponenty, ke kterým je tato práce vztažena. Jelikož jsou tyto komponenty těžko přístupné bez možnosti mazání, nachází se mezi nimi suché spoje a kontakty. Vzhledem k tomu, že se nacházejí v prostředí zatíženém vysokou okolní teplotou, podléhají opotřebení a únavě, které jsou v teoretické části dále představeny. Popsány jsou zde různé modely opotřebení a metody vyšetřující únavu materiálu v cyklicky namáhaném prostředí.

Druhá část je zaměřena na vyhodnocení dat z testů a návrhem vhodných metod pro další posouzení opotřebení na kinematických komponentech. Zpracování těchto dat bylo provedeno pomocí nástrojů Python a Matlab.

Jak již bylo zmíněno, cílem této práce bylo shromáždit data z testů, které jsou zaměřeny na pracovní cykly motoru. Samotné shromažďování testů zabralo nejvíce času z celého procesu této práce. Časově náročná byla také jejich příprava a třídění na pozdější analýzu. To zapříčiňuje především skutečnost, že měření se často provádějí různými akvizičními systémy, liší se pojmenování měřených kanálů, vzorkovací frekvence a podobné.

Na základě předem stanoveného minima požadavků na obsah měřených veličin v testu byly navrženy dvě metodiky charakterizace, jejiž výstupy se liší právě podle toho, kolik dostupných veličin zkoumaný test obsahuje. První metodika je vhodná ke zpracování obecných pracovních cyklů, u nichž předpokládáme, že obsahují pouze naměřená data o zatížení motoru a otáčkách motoru. Tento proces zahrnuje kontrolu pracovního cyklu, ve kterém se musí ověřit, zda je soubor dat kompletní. Nutná je také kontrola jednotek naměřených veličin. Dále je nutné porozumět pracovnímu cyklu, který byl v datech naměřen, abychom byli obeznámeni s jeho vlivem na celkovou životnost komponent. Následným zpracováním a porovnáním dvou pracovních cyklů ze shromážděného souboru dat, je představena úvaha o minimálním požadavku měřených veličin. Zahrnuje to zobrazení naměřených signálů v časové oblasti, 1D a 2D histogramy otáček motoru a zatížení motoru. Na základě 2D histogramu můžeme posoudit, ve kterých segmentech se nejčastěji nacházi daný pracovní cyklus. Výsledek pak může být interpretován například tak, že 12% času testu probíhá při otáčkách, které odpovídají 60-70% z maximálních otáček, přičemž krouticí moment je minimální. Díky těmto informacím můžeme lépe posuzovat dva pracovní cykly mezi sebou, což je hlavním přínosem této metodiky.

Druhým návrhem je analýza pracovního cyklu včetně zpracování polohy aktuátoru. To znamená, že je vhodná pro testy, kde jsou naměřeny otáčky a zatíčení motoru, poloha a zatížení aktuátoru. Díky těmto informacím, které jsou zde oproti první metodice navíc, můžeme pomocí distribučních grafů interperovat více závěrů o daném testu. I přesto, že nemůžeme pozorovat pohyby aktuátoru, zjistíme, že aktuátor vykonává prací, protože je zatížen silou.

Navhované metodiky pomáhají získat více informací o posuzovaném testu. Využitím dřívě meřených testů, výsledky této práce významně přispívají ke zkrácení celkové testovací doby při validaci komponentů vůči opotřebení.

BIBLIOGRAPHIC REFERENCE

KOVAŘÍKOVÁ, Lucie. *Klasifikace provozních zatěžovacích cyklů turbodmychadla ve vztahu k opotřebení kinematických členů.* Brno, 2021. Dostupné také z: https://www.vutbr.cz/studenti/zav-prace/detail/132971. Bakalářská práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Ústav mechaniky těles, mechatroniky a biomechaniky. Vedoucí práce Petr Lošák.

DECLARATION

I hereby declare that I wrote this bachelor’s thesis all by myself under the direction of my supervisor, Ing. Petr Lošák, Ph.D. All used sources are listed in references.

In Brno 21.5.2021 ……..……..…………………………………………..

Lucie Kovaříková

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I would like to express my sincere gratitude to my supervisor, Ing. Petr Lošák Ph.D. for his guidance, advices and given motivation to start learning Python language. Also I am deeply grateful to Ing. Radúz Záhoransky Ph.D. for his insightful comments, suggestions and ivaluable rea-life experience.

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CONTENTS

INTRODUCTION

Correct, reliable, and economical validation is a crucial tool for companies doing business in the automotive industry, both on a subsystem level and on the level of individual components. This is due to the fact that engine subcomponents come from various suppliers. Validation, therefore, is a key stage of product development. Since customers expect their products to meet various requirements pertaining to their life span, efficiency or cost, these products have to undergo thorough testing.

The validation of a turbocharger generally takes several hours. Due to its specific nature, the tests take place directly on the engine. These tests yield large amounts of data related to the engine duty cycle, such as engine speed or engine torque which are the two main subjects of this thesis.
This work aims to collect the data from these tests, review it, determine sorting criteria and propose and evaluate characterisation methodologies of load cycles targeting expected resulting wear of turbocharger kinematics components.

The thesis is divided into two sections – a theoretical segment and a segment devoted to data evaluation. The first part of the theoretical section introduces the reader to turbocharger regulation systems. The second part analyses the reliability of the actuating system of the turbocharger regulation. In the latter section, the focus of the thesis will be on data evaluation and review, provided by using two tools – Python and Matlab. To introduce selected statistical methods, a comparison of several of these tests is offered as well. The proposed and evaluated load cycle characterisation methodologies focused on the expected resulting wear are described and illustrated in a flowchart.

1 PROBLEM DEFINITION

Before it goes into serial production, every component has to be tested and validated on a prototype level. Testing and validation are an essential part of all innovation as they are necessary to scientifically confirm that the component in question is compatible with the operating environment. Under these conditions, we can estimate the lifetime of a component or predict its wear. Simply put, we can confirm that the component meets the requirements for function. However, in real life, test data is not only produced by the company developing the product, but also by various other entities (such as customers or suppliers). This poses a problem, since there is little to no information pertaining to the conditions under which their tests took place.

Generally, tests are designed to solve a particular given problem and they are not meant to serve any other, extra purpose. Engine duty cycle tests are no exception to this rule. Data, sorted out in this thesis, shows that tested variables often have different names, units, or test times in each of the tests. Such tests cannot be classified by simply plotting a graph. These ambiguities are the reason why sorting criteria needed to be defined first, in order to glean as much information as possible from the assorted tests.

As we are well acquainted with the engine duty cycle environment, we can predict what variables the test data will contain. It is, therefore, possible to selectively look for tests that measure engine speed, engine load and time, at the very least. Tests that did not meet these requirements were excluded from this research as incomplete.

By evaluating the resulting data, classification factors and methods, which provide as much information as possible pertaining to the tests from this pre-defined group, could be defined. This could provide valuable information for engineers, especially in terms of the differences between their in-house tests and the tests obtained from their customers. Instead of comparing only the test times alone, we can check information such as load distribution or use the test time to determine the number of load changes, as well. This gives us a much clearer idea of the frequency of the components' movements, as well as their intervals and ranges.

2 REGULATION SYSTEM OF TURBOCHARGER

The turbocharger is a type of rotary machine that improves the efficiency of gasoline and diesel atmospheric engines. It uses the engine's exhaust gases to rotate the turbine wheel, connected to the same shaft as the compressor turbine wheel. This spinning compressor wheel compresses the air from the air inlet. Then, compressed air goes through the air cooler right to the engine cylinder. Turbocharger provides a better air/fuel ratio, which increases the power of the engine. However, this system has to be regulated.

Regulation is an essential part of boosting. Therefore it is required to protect the engine and the turbocharger at high engine speeds, especially gasoline engines operating at higher revolutions per minute (RPM) [1], To illustrate, it is evident that exhaust gas coming from the engine had to be reduced. Lowering the volume of the exhaust gas volume provided a lower rotation speed for both turbines. The reduction is achieved by an adjustable turbine.

This chapter is going to describe the two most used regulation methods – the wastegate fixed geometry turbine and variable nozzle turbine. These turbines are controlled by kinematics components that are relevant to this thesis.

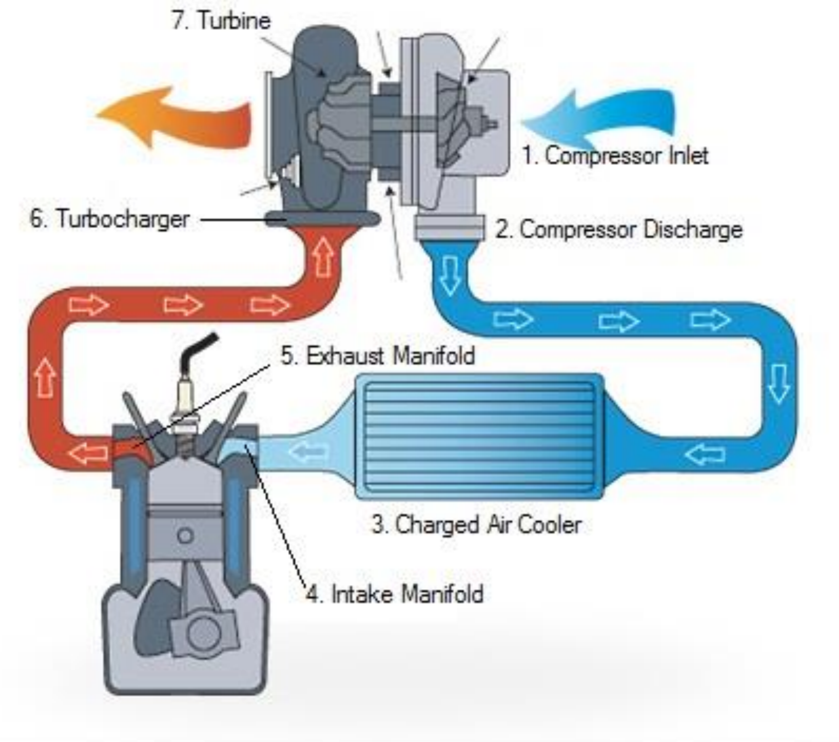

Figure 2.1: Working principle of the turbocharger [2]

2.1 WASTEGATE

In the wastegate turbocharger, the volume of the exhaust gases is controlled through the coordination of actuator and bypass valves. As a result, when the engine is at a low speed, this bypass valve stays shut, so all the exhaust gases go to the turbine wheel. As the engine speed is growing, the actuator opens the bypass valve to control the gases' volume [3]. These movements are provided and managed by an actuator.

2.1.1 External Wastegate

We can divide wastegates by their valve positions. The first type is an external wastegate. This type of valve is a separate mechanism not mounted in the turbocharger. As you can see in Fig. 1.3, wastegate valve (3) is located between the compressor (4) and engine (1) on the exhaust manifold (2). As a result, it is easier to control the boost. For this reason, the external wastegate is used for engines that produce more than 300 kW [4].

Figure 2.2: External Wastegate [5]

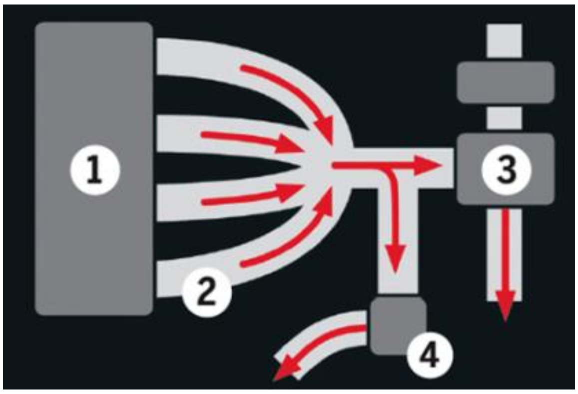

Figure 2.3: Location of External Wastegate [25]

2.1.2 Internal Wastegate

More relevant for kinematics components we are going to be focused on in data evaluation is internal wastegate. This type of wastegate regulation is most common on factory equipped turbochargers. [6] As the name implies, it is located directly inside the turbine housing.

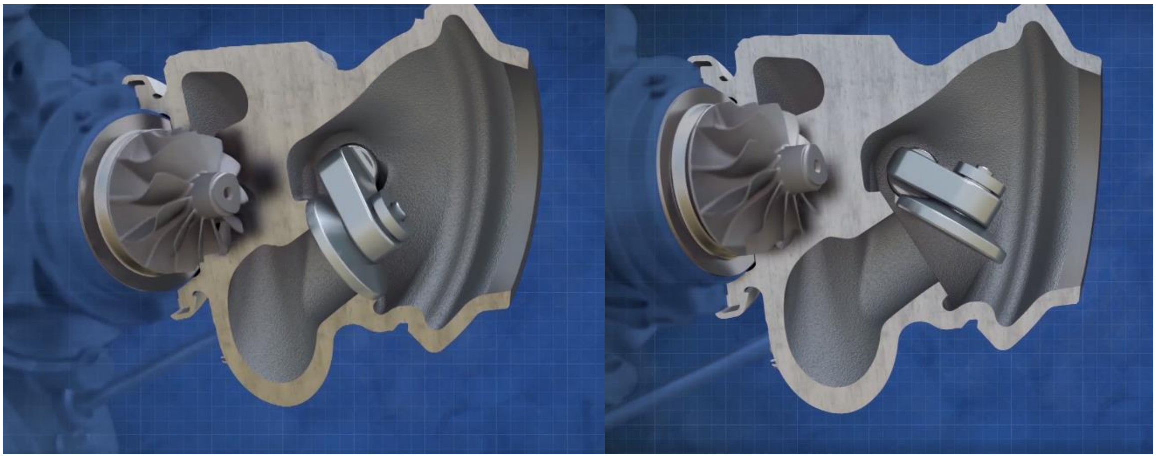

Figure 2.4: Wastegate Valve in a closed and mid-opened position [6]

As described before, when the wastegate valve is closed (Fig. 1.4) whole exhaust gas flow through the turbine. To prevent the turbocharger from over-speeding, the gradual opening of the valve is diverting the mass flow outside of the turbine housing.

2.2 VARIABLE NOZZLE TURBINE

A variable nozzle turbine (VNT) is a system located before the turbine wheel. It consists of vanes united with shafts which are connected by vane arms with a unison ring. This unison ring is associated with the main arm.

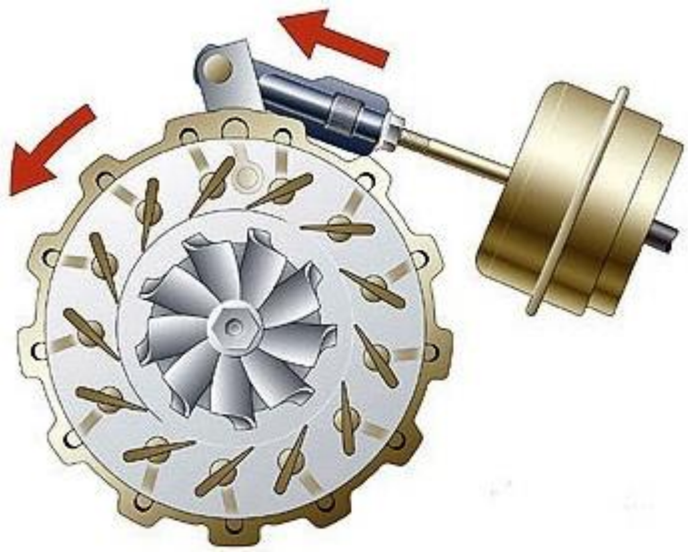

Figure 2.5: VNT Mechanism with Vacuum Actuator [7]

The motion of the vanes is controlled through a kinematic chain from the actuator, which moves the main arm. Tilting of vanes efficiently regulates the exhaust gas coming to the turbine wheel. At high engine speeds, intervane distance is maximal. Thus the exhaust airflow is not restricted and is maximised. Similarly, at low engine speed, intervane distance is minimal. This cause increasing turbine power and boost pressure [8].

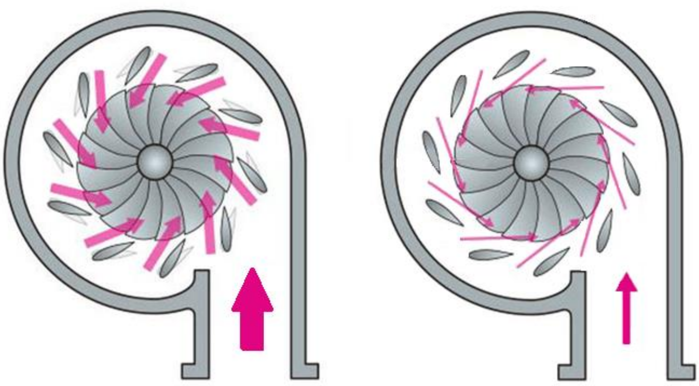

Figure 2.6: Tilt of vanes in low rotation and high rotation speed [9]

Compared with the wastegate method, VNT provides higher turbocharger efficiency in delivering power and higher torque levels at low engine speed [8].

2.3 ACTUATING OF TURBOCHARGER REGULATION

The actuator takes responsibility for all of the motion of the wastegate valve and VNT vanes. Actuators are divided into two types according to their operation:

- pneumatic
- electric

2.3.1 PNEUMATIC ACTUATOR

The pneumatic actuator is working on a simple principle of overpressure. Inside the actuator housing is located rod, spring and diaphragm, which divides this chamber into two parts. To the part without the spring is brought the pressure corresponding to the pressure on the turbine. This put pressure on the spring and compressed it. Through the rod and kinematic chain is the required movement for regulation achieved. Calibration of the actuator is given by spring preload [10].

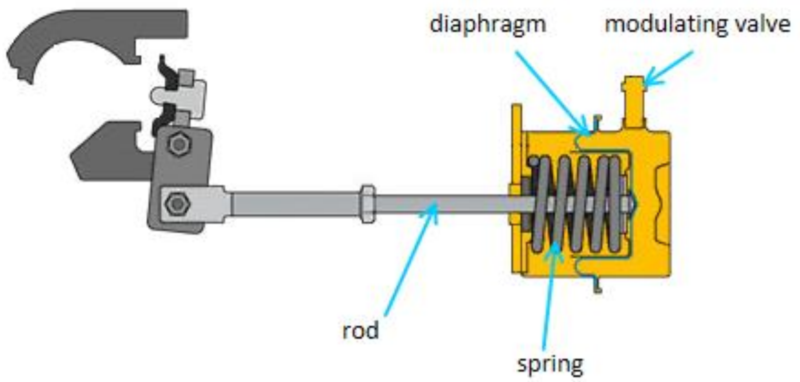

Figure 2.6: Pneumatic actuator section view [10]

There are also vacuum actuators on the market. They work on a similar principle. Instead of overpressure, the vehicle's vacuum pump creates an underpressure in the chamber [11]. Thus the movement of the rod is heading to the opposite side than the overpressure actuator.

Figure 2.7: Pneumatic actuator outside view [12]

2.3.2 ELECTRIC ACTUATOR

Electric actuators are divided according to their movement to:

- LEA – linear electric actuator
- REA – rotary electric actuator

Electrical power is converted into torque by means of a motor. In comparison with pneumatic, electric actuators have a better and more accurate response time of motion. This is achieved by PWM (Pulse Width Modulation) signalisation or databus CAN (Controller Area Network). Both types are calibrated with the engine to ensured the accuracy of movement [11], [13].

Figure 2.8: REA Actuator [14]

Figure 2.9: LEA Actuator [26]

3 RELIABILITY OF ACTUATION MECHANISM

The reliability of the actuation mechanism depends on the reliability of each component. Kinematic components of the regulation mechanism of the turbocharger are subjected in operation to wear and damage resulting from conditions and loads, such as high exhaust gas temperature preventing the use of common lubricants, temperature gradient or dynamic force loading.

The lifespan is greatly affected by the stress environment in which the mechanism operates. Typically:

- cyclic mechanical stress
- thermomechanical stress

Consequently, wear and fatigue damage occurs. For a qualified estimate of the reliability of the actuation mechanism is important to describe this action by scientific methods.

3.1 WEAR DAMAGE

Material wear is an integral part of all mechanical components in operation. Wear can occur by the removal or displacement of material on the solid surface. Especially in places with dry joints without the possibility of lubrication. We can classify wear by the type of relative motion encountered to:

- sliding wear
- impact wear
- rolling contact wear

According to the mechanism of damage, wear could be divide to:

- abrasion (low stress, high stress, gouging, polishing)
- adhesion (fretting, adhesive, seizure, galling, oxidative wear)
- erosion wear
- surface fatigue wear (pitting, spalling, brinelling) [15]

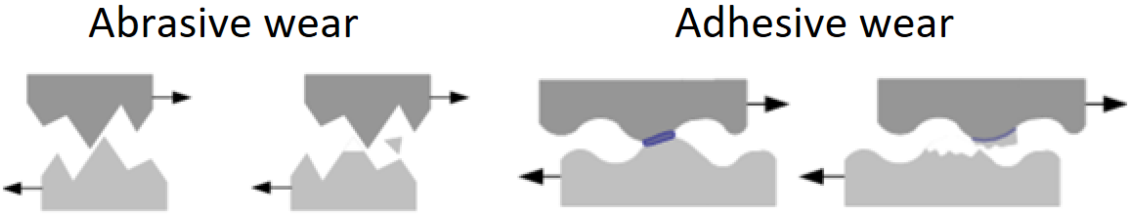

Figure 3.1: Abrasive and adhesive wear [27]

3.1.1 WEAR THEORY MODELS

In engineering practice, to predict material reaction to a stressful situation, wear models are used. The classical wear model takes the sliding speed depending on the rate of material removal, the applied load, the material hardness, and the probability that the material would produce wear particle in a given contact situation. The first model comes from 1860 from German mathematician Reye, who examined wear by defining the contact situation of two loaded bodies. Then through Tabor theory and Holm theory, we get to the last based on the previous ones - Archard's wear equation [16].

ARCHARD WEAR MODEL

The Archard wear model is based on opposing asperities of interaction between contacting bodies. This original model assumed that the rate of volume loss due to wear is linearly proportional to the contact pressure, and velocity is implemented in the program [16], [17].
The relationship is given by:

$$\frac{V}{s} = k \cdot \frac{P}{p_m}$$

Where:

- V: volume of material removed [m^3]
- s: sliding distance [m]
- k: wear coefficient
- P: load applied [N]
- p_m: flow pressure of the material under examination

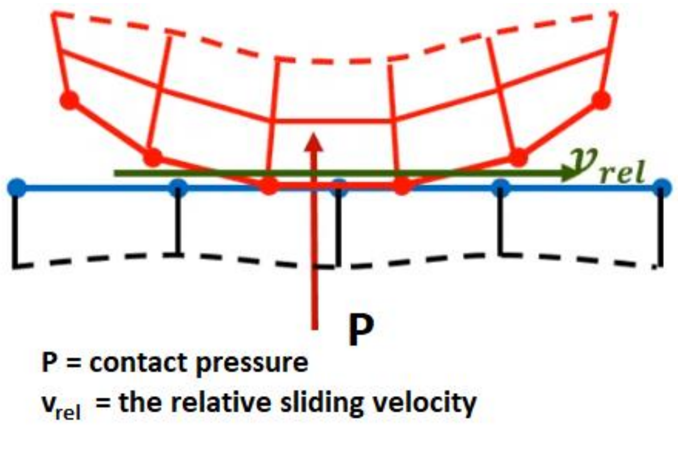

Figure 3.2: Archard wear model [18]

From the classic Archard's wear model, modern mathematical wear models are based. For example, energy balance, mass balance, stress/strain analysis and a contact mechanics approach [16].

3.2 FATIGUE DAMAGE

Fatigue of material is the result of the accumulation of damage by alternating elastic-plastic deformation. It is a process of breaking the cohesiveness of the material over time-varying stress. Significant asymmetrical loading causes permanent softening. We call this cyclic process creep, which leads to a permanent elongation of the components. For this reason, the time course of cyclic loading is an essential part of evaluating the test data [19]. Especially automobiles, tractors and trucks belong to the group subjected to repeated loading and vibration [20].
In the industrial terminology, to distinguish between dynamic loading related to turbo speed, engine pulsation and dynamic cycling related to changes of engine load, fatigue mechanism is further divided into:

- low-cycle fatigue
- high-cycle fatigue

3.2.1 FATIGUE LIFE PREDICTION METHODS

Fatigue life prediction methods predict life in a number of cycles to failure and define the type of fatigue by the number of cycles N for a specific level of loading. If the number of cycles is from 1 to 10^5, the cycle is low-cycle fatigue. And if the N is higher than 10^5, the fatigue is high-cycle [19].

STRESS-LIFE METHOD

The stress-life method is mainly used for high-cycle applications because it is based on stress level only and does not consider a more detailed analysis of the plastic deformations. It is easy to be implemented for a wide range of design applications and adequately represents high-cycle applications. The dependence of the voltage amplitude of the constant harmonic loading of a smooth, perfectly machined test specimen of normalised dimensions on the number of oscillations up to fracture N is described by a Wohler curve, mostly called the S-N diagram. This diagram distinguishes load regions to low cycle, high cycle fatigue, also a finite-life and infinite-life region. For asymmetric cycles is used Haigh diagram [21], [19].

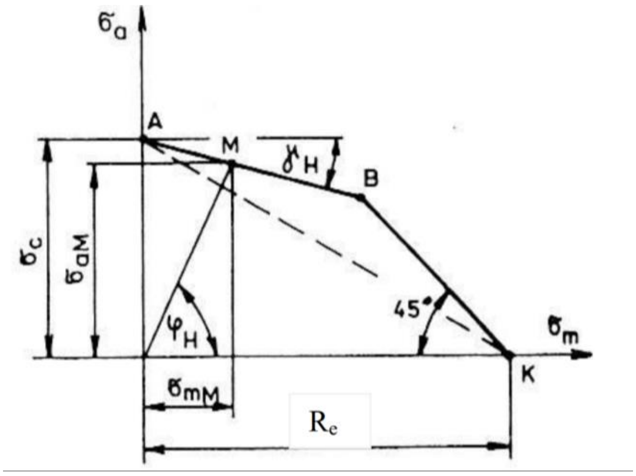

Figure 3.3 Haigh diagram [19]

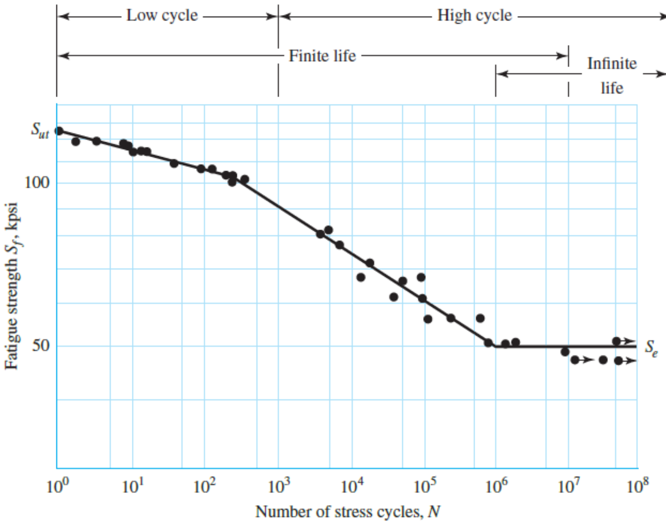

Figure 3.4: S-N diagram [21]

MINER'S RULE

The simplest method of cumulative damage model is Miner's rule. According to this rule, if the component is loaded with k different stress levels, n_i cycles with a stress amplitude S_i is equivalent to consuming n_1/N_1 of the fatigue resistance [22]. It implies that failure occurs at the time that

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

Where:

- n_i: number of the cycles accumulated at stress S_i
- C: fraction of life consumed by exposure to the cycles at the different stress levels

The condition of the failure occurring is generally met when the damage fraction C reaches one. [23] This condition is given by Miner's rule that assumes the damage done by each stress repetition at a given stress level is equal to the stress level at the last stress level [24].

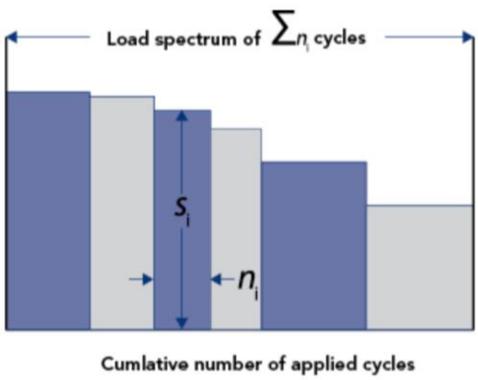

Figure 3.5: Miner's rule [24]

4 TEST DATA EVALUATION

In cooperation with Garrett Advancing Motion company, test from 3 product application were gathered. Collected data contain approximately 1900 seconds of test time in a various condition of the load. This sample is large enough and suitable for assessing the proposed data processing method. Preparation for data evaluation included manually sorting these tests, such as looking for quantities that need to be obtained in the test. An overview has been created. The main attributes of this overview are the values measured in the test and the total time of each test; this facilitates orientation in the collected data. A couple of tests were chosen to introduce a review of data and the statistic method used for processing.

4.1 SOFTWARE

We were considering which software would be the best choice to be used for data processing and review. The selection was as follows:

- Minitab
- Matlab
- Python
- DIAdem

Minitab is a statistics package that provides data analysis whit built-in functions. However, this software was not selected because it is not suitable for such a large amount of data as duty cycle included, speaking of thousands of rows.

As we need to find software for large data sets, software DIAdem was considered. It is optimised for the post-processing of measurement data. Though it sounds like perfect software for our application, the number of licences available was decisive, and this software was not chosen.

From selection, two software were chosen – Python and Matlab. The reason for using Python is that it is free and open-source. It is easy to code and learn its language. An example of the Python programming language and environment of Pycharm, in which the processing took place, can be found in the attachments. Python also offers lots of free math and statistical libraries. For the processing, we used the most:

- Pandas – data analysis library
- NumPy – numerical library
- SciPy – scientific library
- Matplotlib – plotting library

4.2 GENERIC DUTY CYCLE DATA PROCESSING

For better visualisation and orientation in this process, the below flowchart was created.

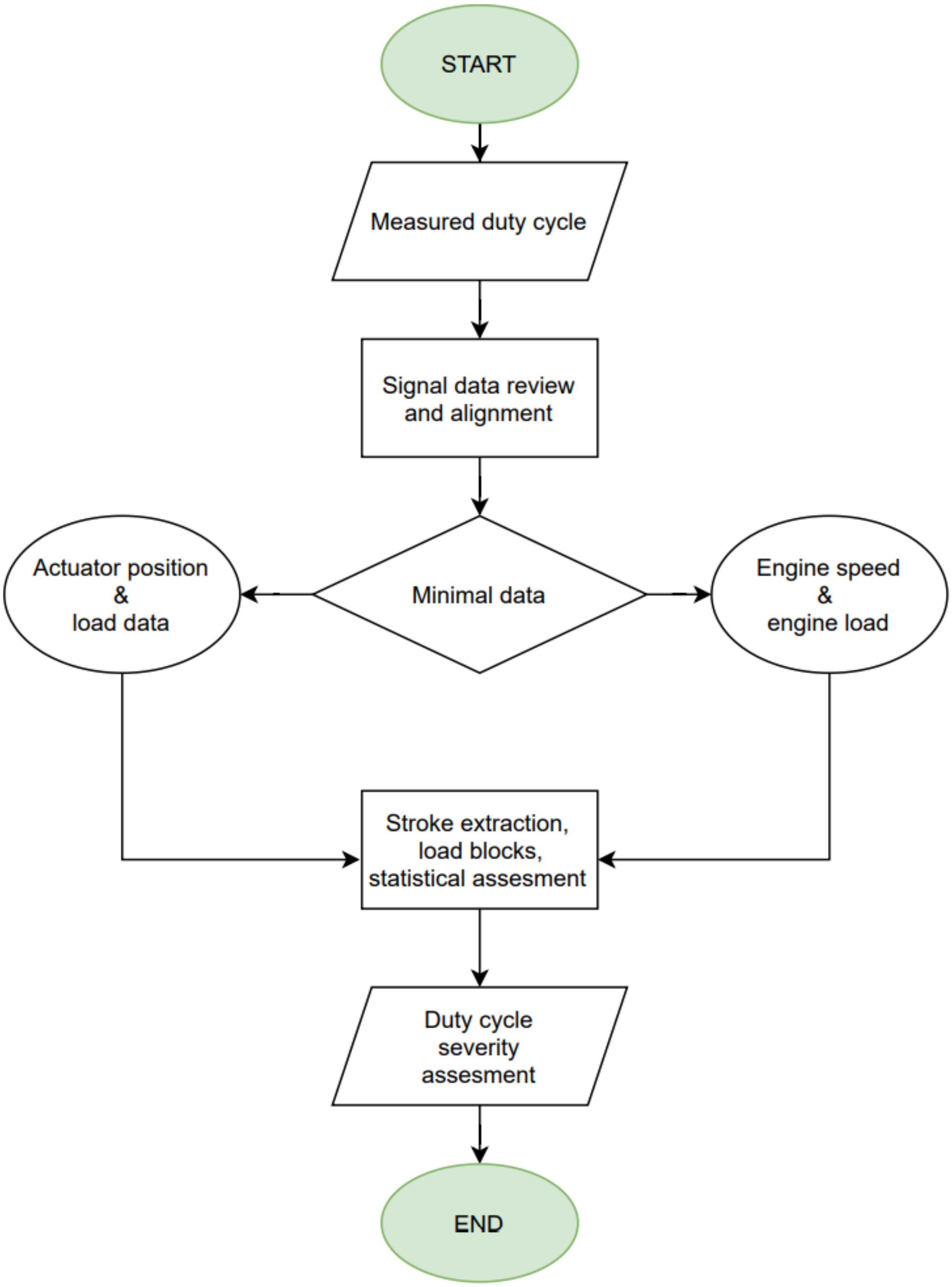

Figure 4.1 Flowchart of process proposal

4.2.1 Signal data review and alignment

The whole process starts with the received measured duty cycle. The first step is to check and align on measured signals. It is necessary to assess whether the data is complete or some information is missing. Also in this step should be included checking the units of the measured quantities. Most importantly, should be checked:

- pressures (mbar, relative vs absolute, dynamic vs static)
- sampling frequency
- actuator position:
  - units (volts, mm, %)
  - end stop value (fully closed position)

As mentioned, the lifetime of the component is assessed based on the history of cyclic loading. For this reason, it is vital to understand duty cycle relevance for the lifetime (scale factor). This should be done in step two. It has to be decided if it is:

- average duty cycle
- a part of typical load cycle
- exceptional duty cycle – occurs rarely (cold start, special regime)
- accelerated duty cycle – decision in what sense of acceleration
  - high thermal load – running high engine speed/high engine load
  - potentially high dynamic load – running many transients low-high load

4.2.2 Setting minimum data requirements

Because the tests can be incompleted, requirements for minimal information defined as engine speed, engine torque/load and min 10 Hz sampling has to be set in step three. This includes:

- **Scope of analysis**
  - Transient, even small changes of load can be related to actuator movements.
  - Engine load steps are attributed to peak stresses in the linkage
  - High load dwell points are attributed to thermal load (high temperature, however, does not necessarily correlate to high wear rate) and potentially high vibration levels.
  - Idle periods can contribute to excessive vibration load of linkage.

- **PLOT SIGNALS IN TIME DOMAIN**

Figure 4.2:Signals in time domain – test 1

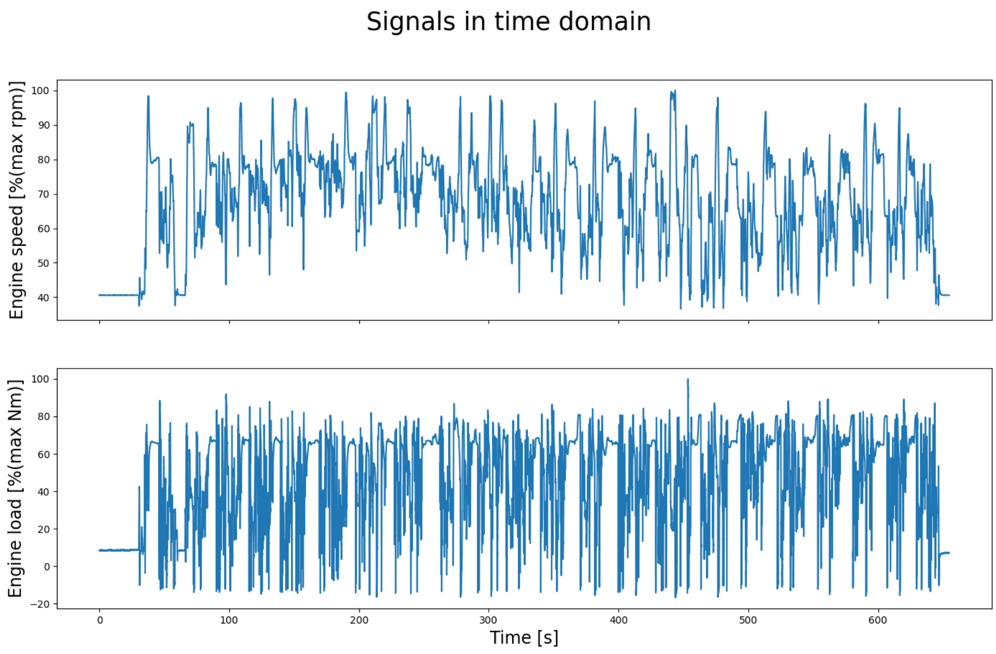

Figure 4.3: Signals in time domain – test 2

Figures 4.2 and 4.3 show engine speed and engine load as a function of time. Both quantities were converted to percentages, where 100% corresponds to their maximum values. Even though we can estimate how the actuator would behave, these graphs do not give any specific information. We can also see much noise caused by the measurement, which is needed to be filtered.

- **1D HISTOGRAM OF ENGINE SPEED AND ENGINE LOAD**

Engine speed

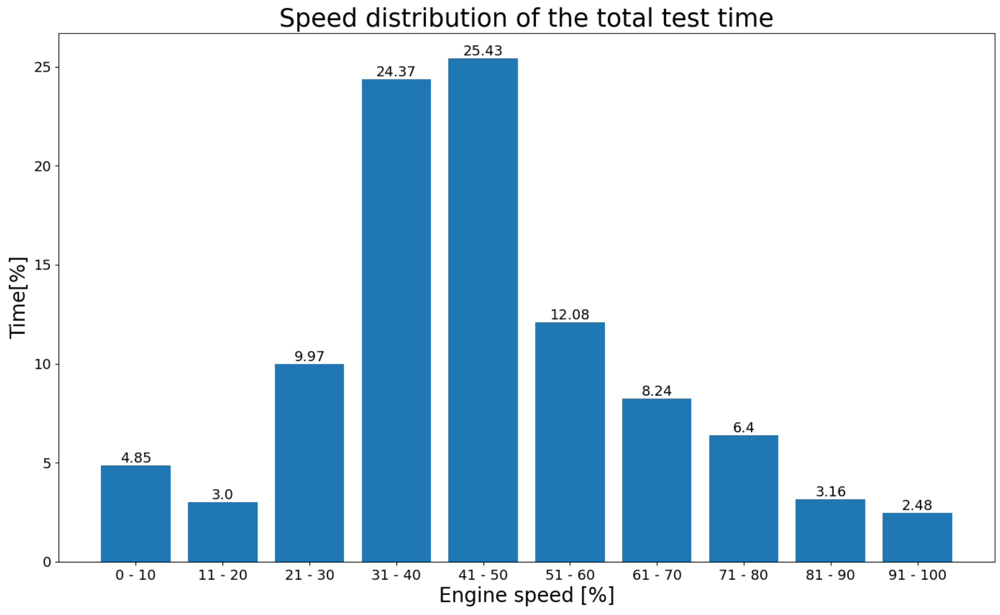

Figure 4.4: 1D histogram of engine speed – test 1

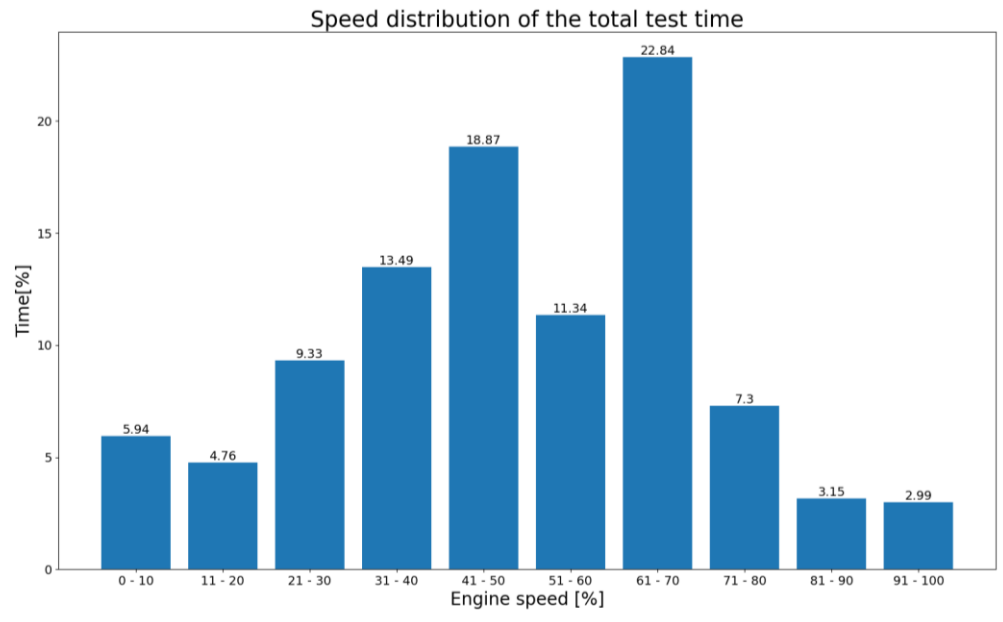

Figure 4.5: 1D histogram of engine speed – test 2

Figure 4.4 and figure 4.5 are presenting the engine speed distribution of the total test time, where 0% represents idle, and 100% represents maximum engine speed in the test.

Engine load

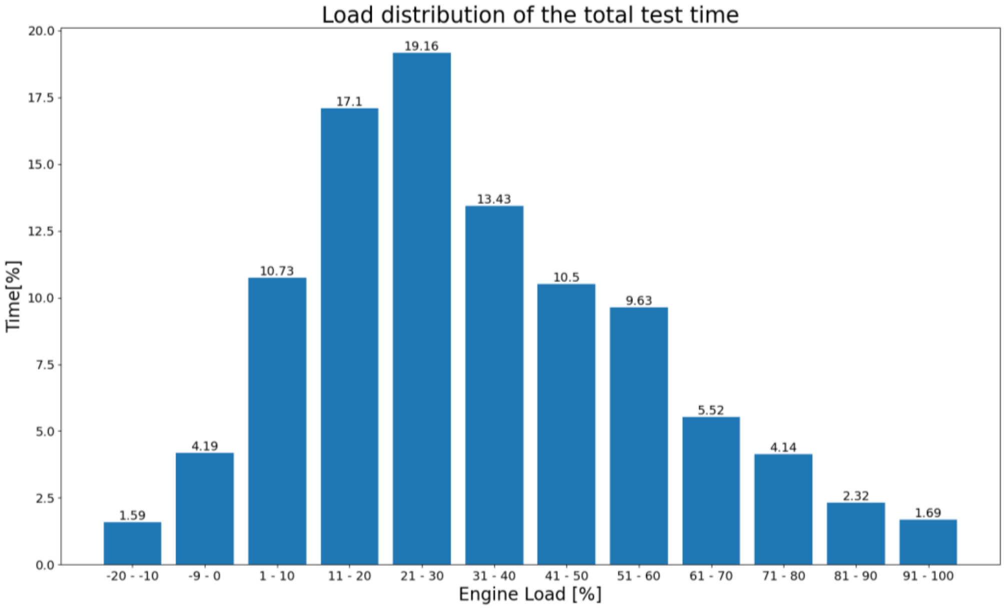

Figure 4.6: 1D histogram of engine load – test 1

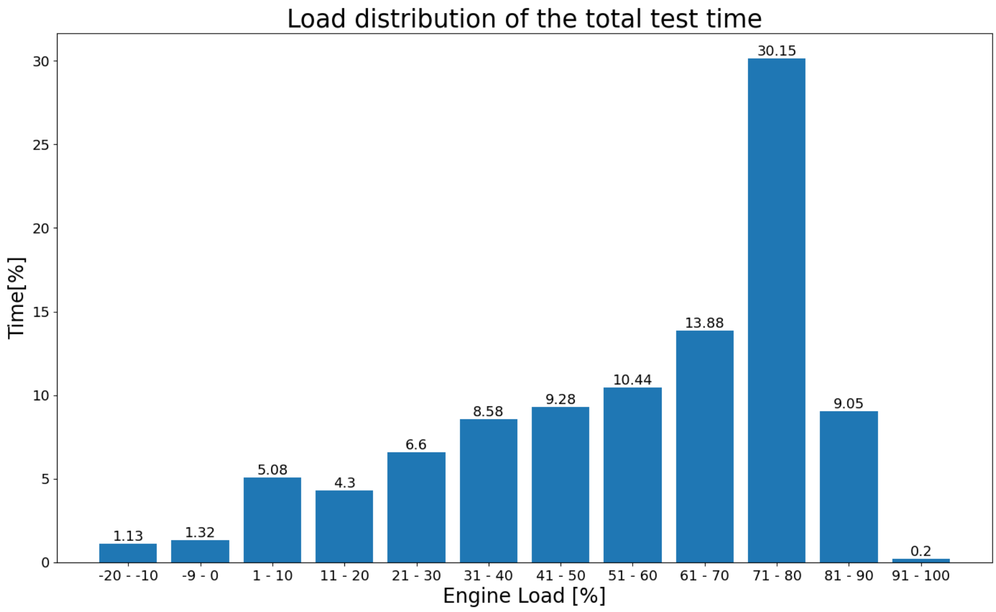

Figure 4.7: 1D histogram of engine load – test 2

In the same way as previous figures, figure 4.6 and figure 4.7 show the 1D histogram this time for the engine load. Negative values of percentages on the x-axis express motoring/braking, 100% value represents the peaks of load.

- **2D HISTOGRAM OF ENGINE SPEED AND ENGINE LOAD**

In figures 4.8 and 4.9, the point distribution of compared tests 1 and 2 can be seen. This shows in what operational points is the system operating and how often.

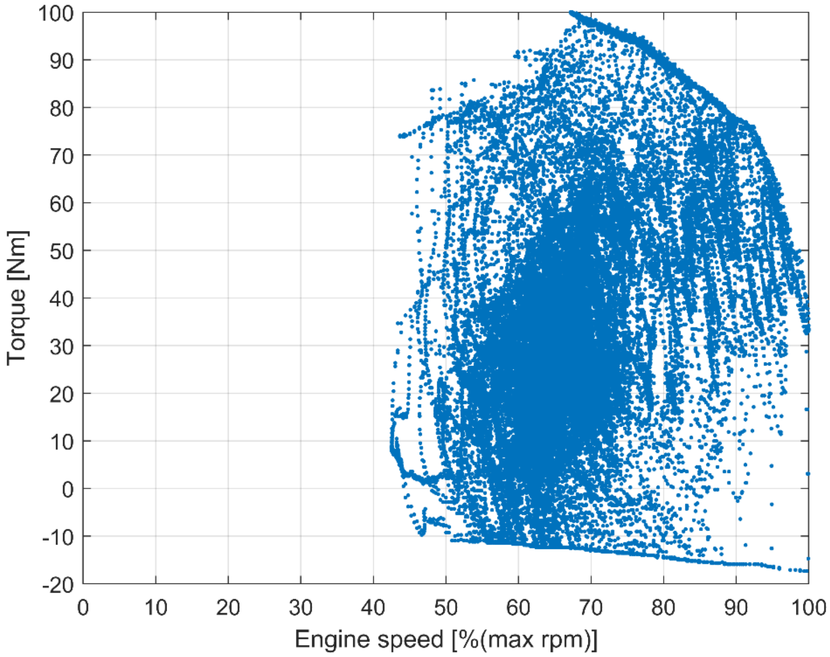

Figure 4.8: Point distribution – test 1

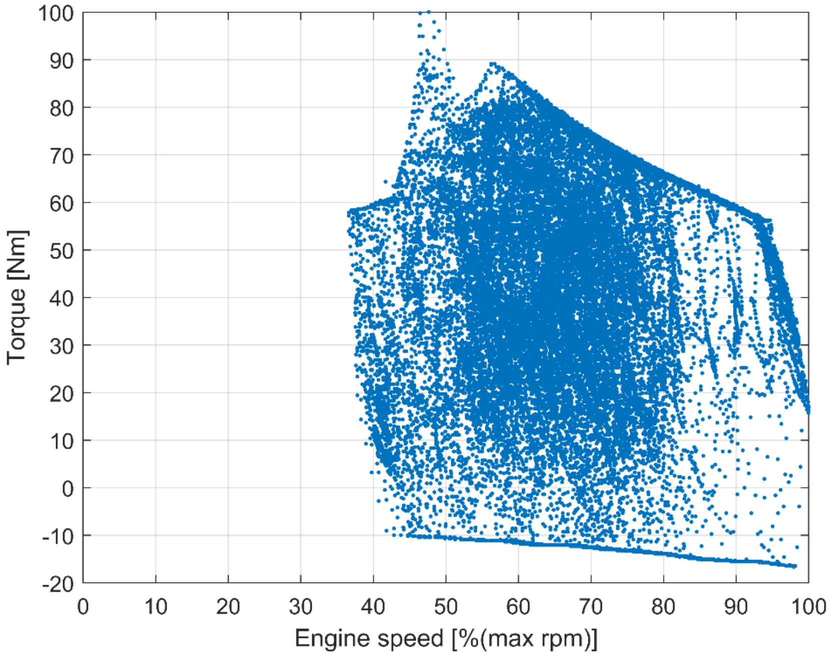

Figure 4.8: Point distribution – test 2

These two below charts represents the incidence of engine speed in specific segments of the engine operative spectrum. In test 1, shown in figure 4.9, we can observe that the highest load occurs at segment 60-70% of max engine speed under load 20-30 Nm. If we compare this test with test 2, which operates mostly under load 60-70 Nm at higher engine speed with higher incidence, it is evident that components from test 2 are exposed to considerable higher stress.

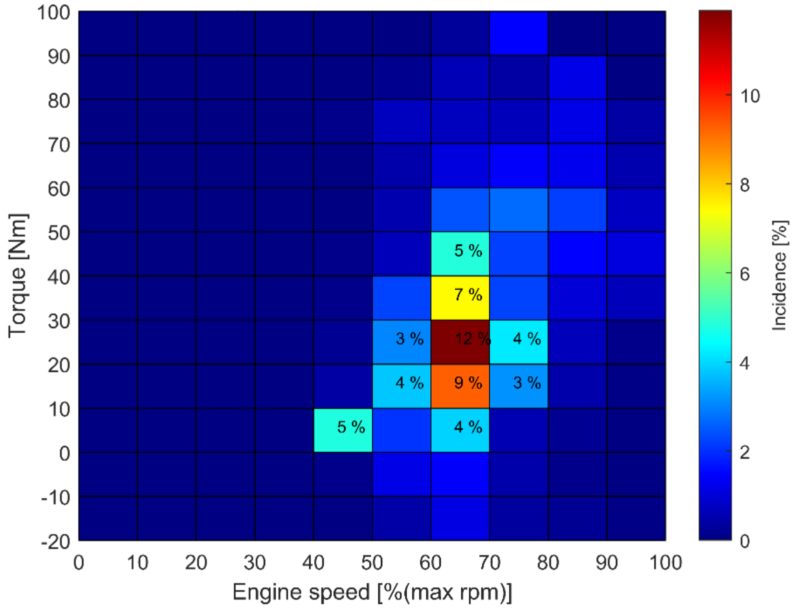

Figure 4.9: 2D histogram of engine speed/engine load – test 1

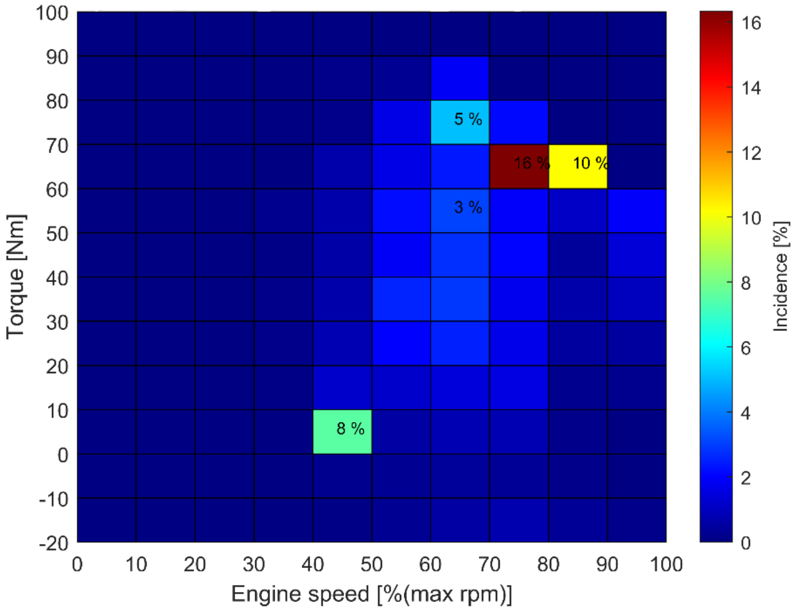

Figure 4.9: 2D histogram of engine speed/engine load – test 2

As proof of previous, the distribution of engine speed/engine load correlates with actuator movement - test 1 and 2 are plotted in the same distribution related to actuator cumulative stroke distribution.

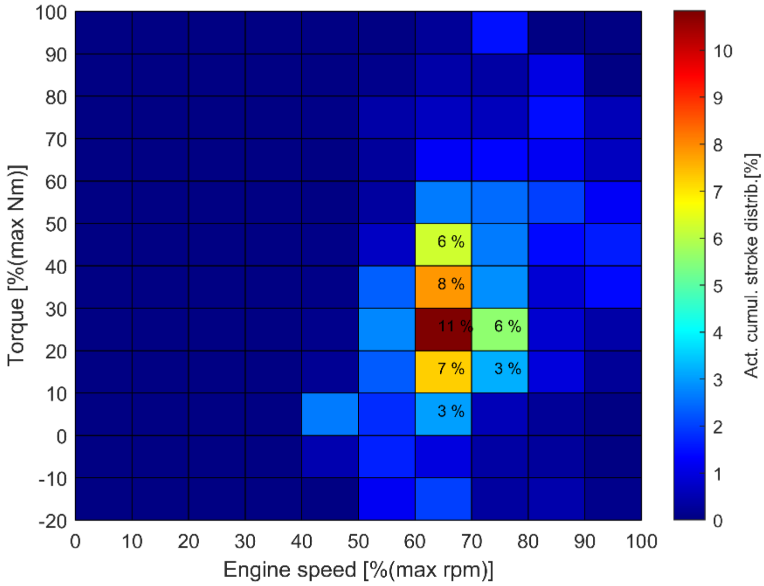

Figure 4.10: 2D histogram of engine speed/engine load depending on actuator cumulative stroke distribution – test 1

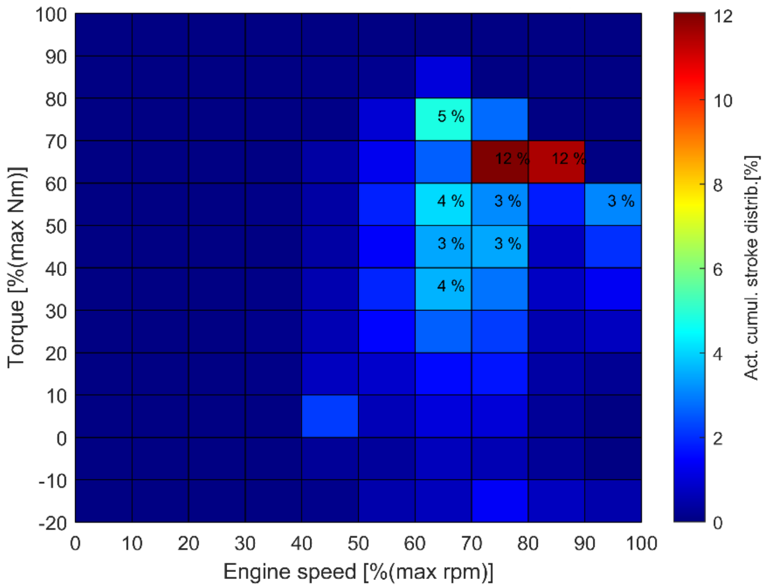

Figure 4.11: 2D histogram of engine speed/engine load depending on actuator cumulative stroke distribution – test 2

- **UNDERSTANDING OF TRANSIENTS**

  To eliminate measurement noise and sharp changes, which would generate extreme values of the first derivative (rate of change), applying the floating mean filter on data should be considered. A width of a floating window should not exceed the shortest transient change. Recommended is 0.10 s – 0.25 s. In Python, it is provided by a function from Pandas library called rolling mean. It takes a window of sequential values from the data, calculates its average and saves it. It goes to the next window until it goes through the whole array of data. The whole algorithm is described as follows:

$$SMA = \frac{A_1 + A_2 + \cdots + A_n}{n}$$

Where:

- A: average in period n
- n: number of time periods [25]

The result of the process is shown in Figure 4.12 below, originating from test 1. It has been zoomed in for better visibility.

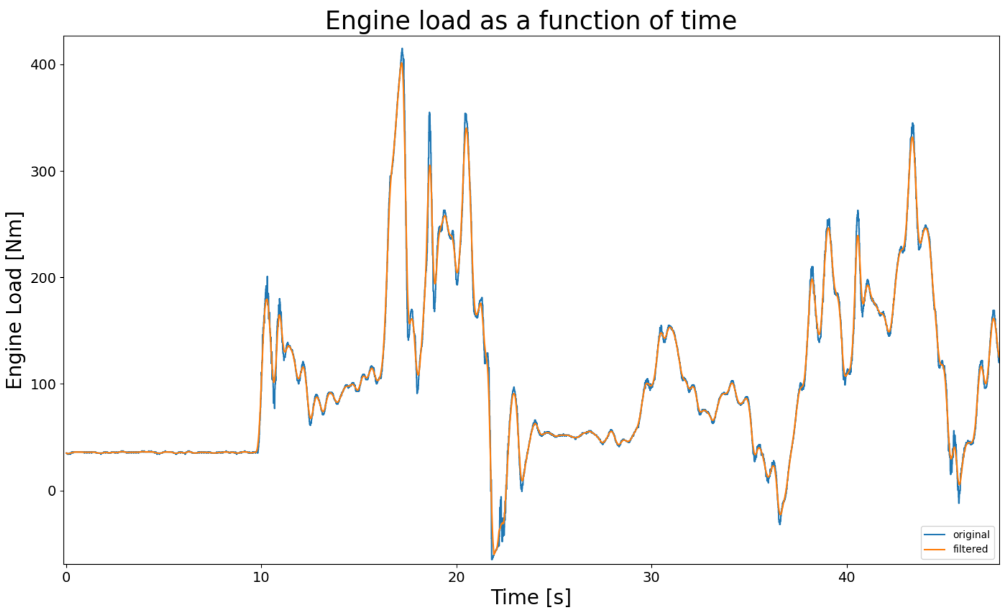

Figure 4.12: Example of filtered data by moving average

Further, the decision on applying a low pass filter for small oscillations should be made. Based on the heuristic estimate is optimal to filter out signal noise, not to filter out real small oscillations in the load that can indicate control system instability etc. Recommended is up to max 1% of range.

After preparation data, it is proper to:

- Identify extremes in signals (min-max)
- Count min/max distribution
- Identify sub-transients between min-max – where the load target (accelerator pedal) position changed – sub-transients:
  - By splitting segments between min/max into subsegments if slope changes above the threshold – identifying change
  - Usage of derivative – rate of change of engine load

4.3 DUTY CYCLE ANALYSIS INCLUDING ACTUATOR POSITION

The start of processing data with actuator position include does not differ from the generic duty cycle processing. However, while checking out the units of measured quantities, it is necessary to convert the actuator position signal to relative 0-100% from the reference end stop (e.g. convention is to use 100% for fully closed VNT). Assurance if the consistency is kept when comparing different measurements/engine data is required.

Applying the filter to eliminate measurement noise is recommended also for actuator position. The proposed range of window for floating mean is from 0.1 to 0.25 s. In figure 4.13 is shown, how the range of window influence resulting filtered data.

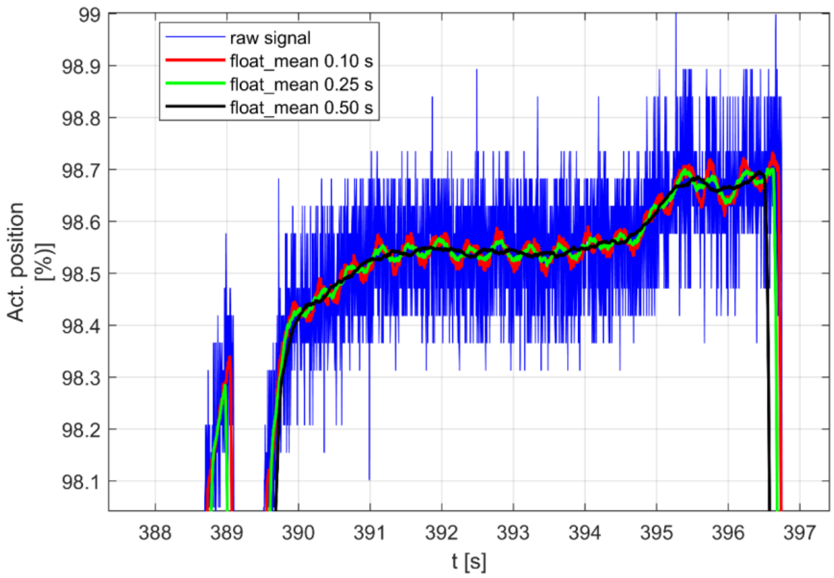

Figure 4.13: Filtered data of actuator position

Further is proper to make extraction of strokes and creation of load blocks. The following methods are recommended:

- Identify extremes in signals: min-max
- Usage of min-max counting method (rain flow or similar)
- Distribution analysis: e.g. from-to, distribution of strokes and mean values etc.

To assess the correlation between actuator position and actuator load, the test where these two channels were measured was chose. The plot of signals in time domain is shown in figure 4.14:

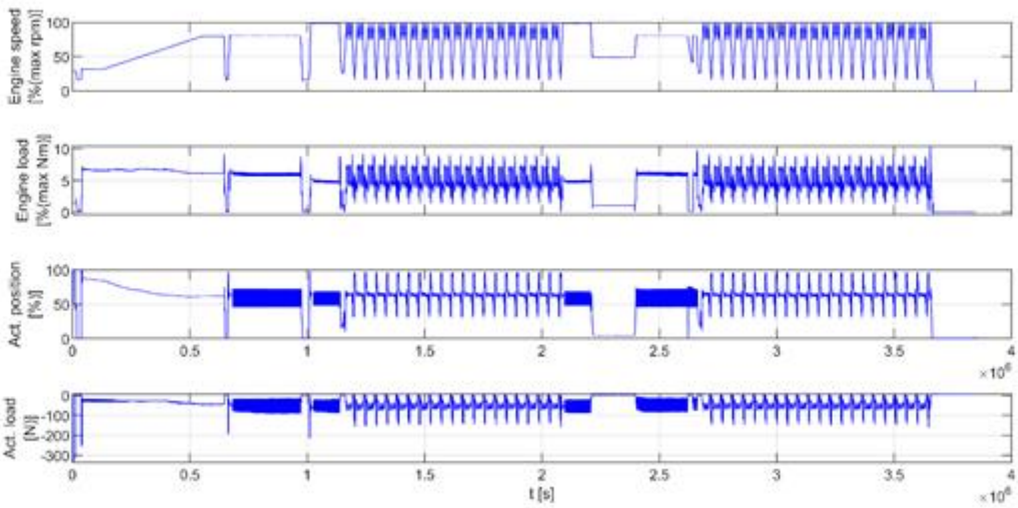

Figure 4.14: Signals in time domain – test 3

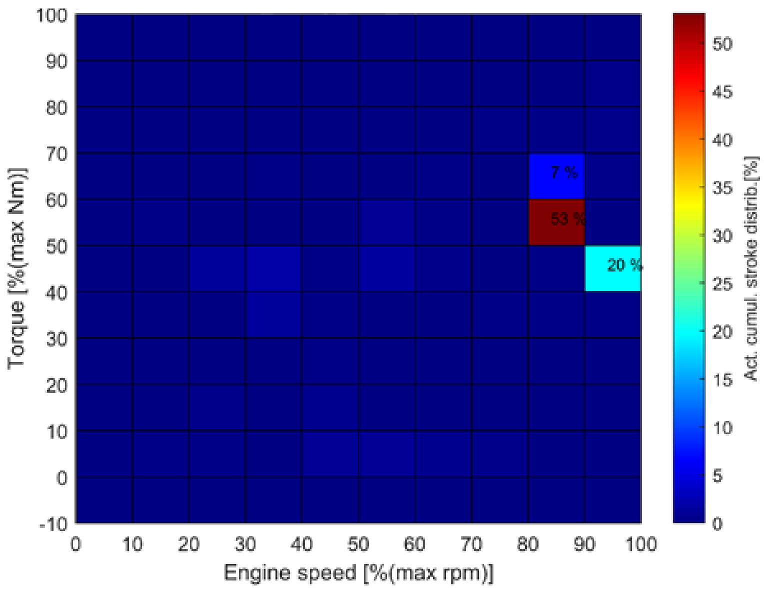

Figure 4.15: 2D histogram of distribution of actuator cumulative movement in engine map

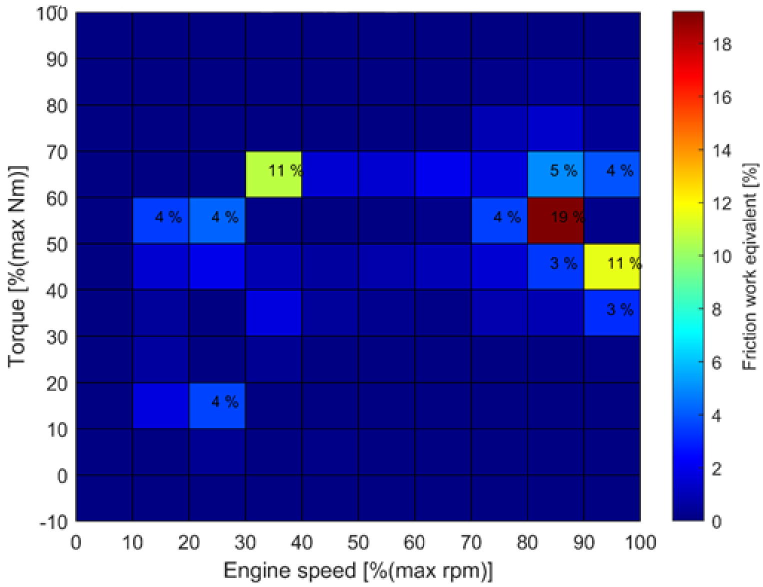

Figure 4.16: 2D histogram of distribution of friction work equivalent

Figure 4.15 shows 2D histogram of distribution of actuator cumulative movement in engine map. Clearly, most of the movement happens in specific engine operational point. Compared with 2D histogram from figure 4.16 of distribution of friction work equivalent (which represents product of movement and force), it gives us much fewer points corresponding to actuator stress.

4.3.1 ACTUATOR STROKE COUNT AND DISTRIBUTION

If actuator position signal is available, interesting information can be obtained from decomposing signal into stroke segments by first filtering out threshold noise, identifying local extrema (min and max) and substituting original raw signal with signal consisting of strokes. This is alternative to conventional rain flow analysis that is more suited for the scope of assessment of the loads the kinematic linkage is exposed to. An example of this extraction - here original recorded signal of position of the actuator is replaced by set of straight lines between extrema (strokes).

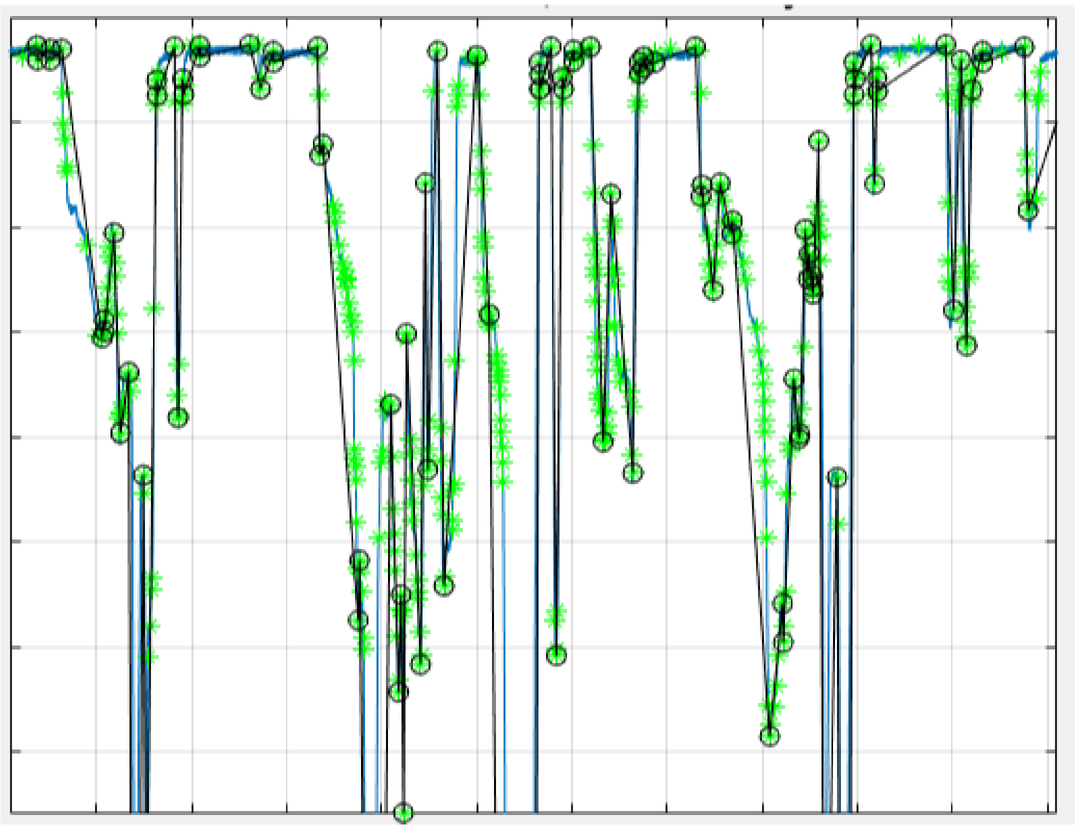

Figure 4.17: Example of extraction

The most straightforward assessment then is to count total number of strokes and norm it to unit time or driven distance (e.g. 1 hour). The assumption behind is that the pure sliding wear is proportional to accumulated friction path ("distance traveled") and fatigue fraction of wear is related to amount of load reversal (simplified assumption that each stroke accounts for 1 load reversal)

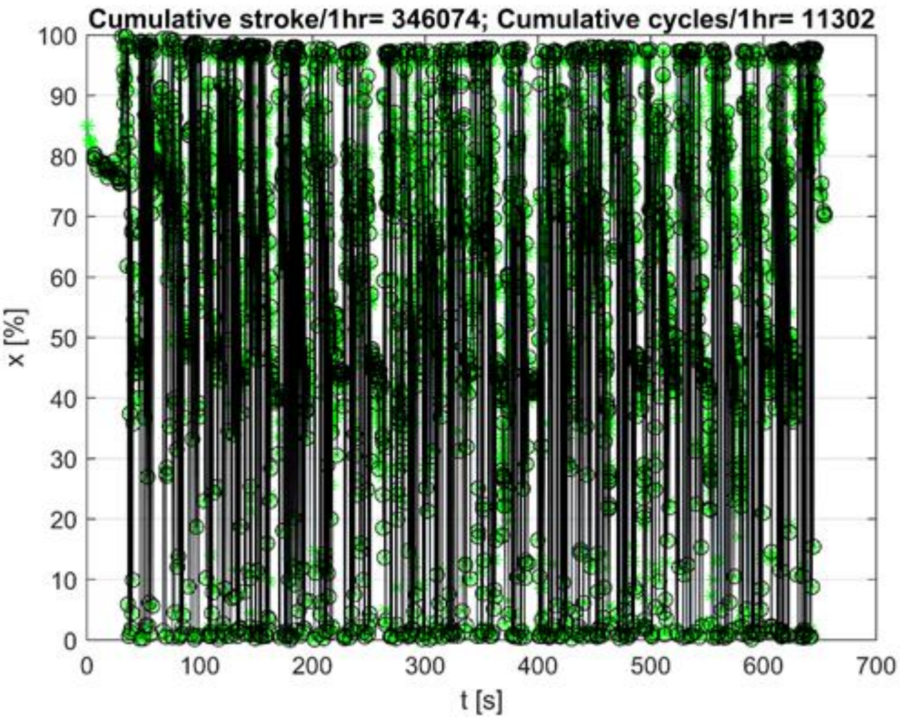

Figure 4.18: Example of extraction

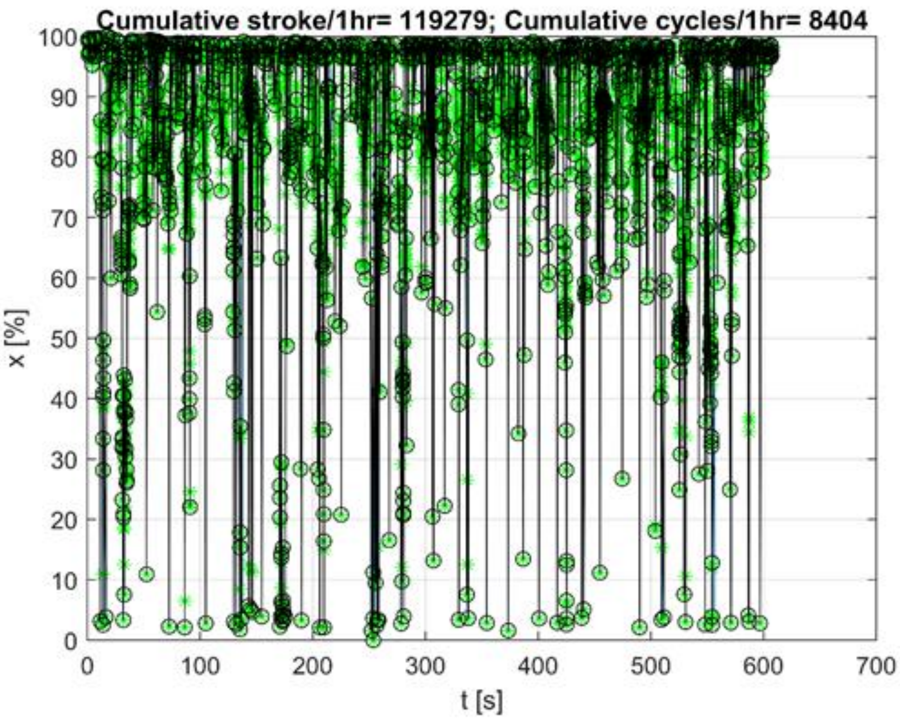

Figure 4.19: Example of extraction

An interesting type of analysis is 2D statistical distribution of strokes by tracking, segmenting the range and counting where i-th stroke starts (x axis) and where it ends (y axis). Here the region around diagonal (left bottom to right top) corresponds to small strokes around mean position, Top right square (100 %) are small strokes around fully closed position and top left and bottom right correspond to full strokes (0%-100%-0%).

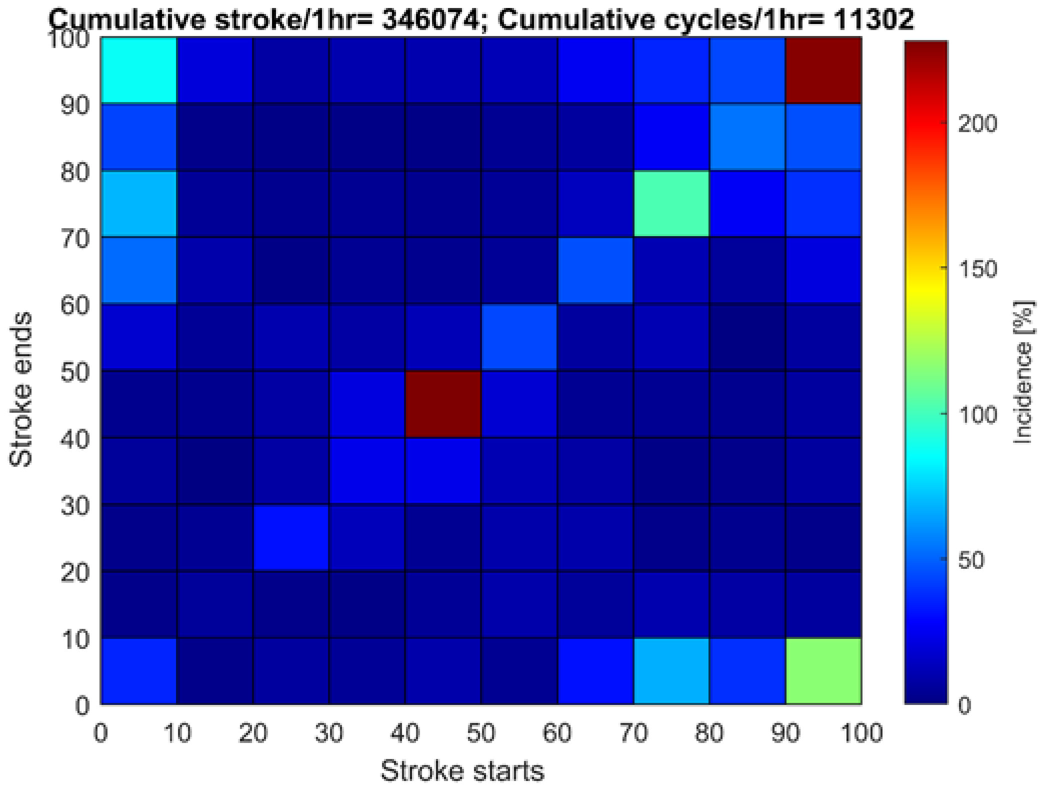

Figure 4.20: 2D statistical distribution of strokes by tracking

CONCLUSION

The goal of this thesis was to gather test data from a durability test, which corresponds with the wear of kinematic components, and to review, sort and classify it based on wear severity and duration. To achieve this, two methods of characterisation of load cycles targeting expected resulting wear were proposed, first.

The most time-demanding stage of this research was the collection of data. Sorting and preparation for the analysis took much time as well, which is mostly due to the fact that measurements are frequently performed with different acquisition systems, channel names, sampling frequency etc.

Based on the pre-established minimum data requirements, this thesis proposes two main characterisation methodologies. They differ depending on which information is assumed to be contained in the test. The first method is used to process general duty cycles which are expected to only contain data pertaining to engine load and engine speed. Here, the processing stage also involves a duty cycle signal data review and alignment, where it is verified that the data set is complete, as well as an assessment of the measured quantities. Furthermore, it is necessary to understand the type of the duty cycle we encounter and how it affects the lifetime of components. The setting of minimum data requirement is introduced by processing and comparing two duty cycles from the gathered data set. Plot signals in the time domain, 1D and 2D histogram of engine speed and engine load are shown here. Based on the 2D histogram, we can observe which segments a given duty cycle is most frequently located in. For example, 12% of the total test time runs at 60-70% of the maximum engine speed with only a minimal torque. This is the main output of this method of comparison, through which we can contrast two duty cycles with each other.

The second proposal presented in this thesis is a duty cycle analysis that incorporates actuator position. This makes it well-suited for tests that also take into account engine speed, engine torque and measured actuator position and load. This extra information about the actuator gives us more details that we can observe in the distribution charts. Such charts are far more informative, since they contain information about distribution based on the position and load of the actuator. Despite the fact that we can observe no actuator movements, the actuator still has to perform work because it is under a huge load.

The two methods proposed in this thesis help us to glean more information about tests we desire to assess. The results of this thesis have the potential to greatly shorten the total duration of component durability testing, since they make it possible to use older tests as well.

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ATTACHMENTS

```python
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

# ______________________IMPORT FROM CSV____________________________________________
data = pd.read_csv("data\location\data_file_name.csv", decimal=',')
data = data.astype(np.float32)
data.rename(columns={'t[s]': 'time', 'ENGSPD[rpm]': 'engine_speed', 'PS_trq_val[Nm]': 'torque'}, inplace=True)
# ________________________________________________________________________

# ____SIZE OF WINDOW for floating mean method____
time_1 = data["time"][0]
a = 0
for i, row in enumerate(data.itertuples(), 1):
    if (row.time - time_1) <= 0.5:
        # print(i, row.time)
        a = a + 1
        timehp = row.time
        print('toto je velikost vzorkovaciho okna: ' + str(a))
    else:

        break

# ______________data filtering _______________________
time_f = data.time.rolling(a, min_periods=1).mean()  # center=True
load_f = data.torque.rolling(a, min_periods=1).mean()
rpm_f = data.engine_speed.rolling(a, min_periods=1).mean()

# _______________ conversion data to percentages ___________
var_data = pd.DataFrame(list(zip(time_f, load_f, rpm_f)), columns=['time', 'load', 'speed'])
load100 = max(var_data["load"])
speed100 = max(var_data["speed"])
print(load100)
print(speed100)
x = []
y = []
load = []
speed = []
for row in var_data.itertuples():
    load = abs((row.load * 100)/ load100)
    print(load)
    x.append(load)

    speed = (row.speed * 100)/ speed100
    y.append(speed)

# Creating plot
plt.hist2d(x, y, bins=[10,10], cmap=plt.cm.turbo)
plt.title("Engine speed/Engine load distribution",size = 20)
# Adding color bar
cb = plt.colorbar()
for t in cb.ax.get_yticklabels():
    t.set_fontsize(14)

plt.xlabel('Engine load [%]',size = 20)
plt.ylabel('Engine speed [%]',size = 25)
plt.xticks(fontsize=14)
plt.yticks(fontsize=14)
plt.show()
```

Example of Python programming language and Pycharm environment